A COMPACT S – BAND FRONT-END RECTENNA FOR WIRELESS POWER TRANSFER APPLICATION

IKHWAN PERANGGI POHAN

UNIVERSITI TEKNOLOGI MALAYSIA

PSZ 19:16 (Pind. 1/97)

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN STATUS TESIS♦

JUDUL : **A COMPACT S-BAND FRONT-END RECTENNA FOR WIRELESS POWER TRANSFER APPLICATION**

SESI PENGAJIAN : **2005/2006**

Saya **IKHWAN PERANGGI POHAN**

(HURUF BESAR)

mengaku membenarkan tesis (~~PSM~~/Sarjana/~~Doktor Falsafah~~)* ini disimpan di Perpustakaan Universiti Teknologi Malaysia dengan syarat-syarat kegunaan seperti berikut :

1. Tesis adalah hakmilik Universiti Teknologi Malaysia.
2. Perpustakaan Universiti Teknologi Malaysia dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. ** Sila tandakan (√)

[ ]	SULIT	(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)
[√]	TERHAD	(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)
[ ]	TIDAK TERHAD	

Disahkan oleh

(TANDATANGAN PENULIS)

(TANDATANGAN PENYELIA)

Alamat Tetap :

JL. KERTAS NO.20 MEDAN

20118, SUMUT, INDONESIA

PROFESOR MADYA DR MAZLINA BINTI HJ ESA

Nama Penyelia

Tarikh : 28 Disember 2005

Tarikh : 28 Disember 2005

CATATAN : * Potong yang tidak berkenaan.

** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh tesis ini perlu dikelaskan sebagai SULIT atau TERHAD.

♦ Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

UNIVERSITI TEKNOLOGI MALAYSIA

81310 UTM SKUDAI,
JOHOR DARUL TA'ZIM,
MALAYSIA

Cert. No. 403980

TELEFON : +607-5533333 Laman Web : www.fke.utm.my TELEFAX : +607-5566272

FAKULTI KEJURUTERAAN ELEKTRIK

2 January 2006

RUJUKAN KAMI (OUR REF) :

LIBRARIAN
Perpustakaan Sultanah Zanariah
Universiti Teknologi Malaysia
UTM Skudai
Johor

Sir,

CLASSIFICATION OF THESIS AS RESTRICTED
TITLE : "A COMPACT S-BAND FRONT-END RECTENNA FOR WIRELESS POWER TRANSFER APPLICATION"
NAME OF AUTHOR : IKHWAN PERANGGI POHAN, ME033017

Please be informed that the above mentioned thesis entitled **"A COMPACT S-BAND FRONT-END RECTENNA FOR WIRELESS POWER TRANSFER APPLICATION"** or in Bahasa Melayu **"REKTENA PADAT HUJUNG-DEPAN JALUR-S BAGI KEGUNAAN PINDAHAN KUASA TANPA WAYAR"** be classified as RESTRICTED. The reasons for this classification are

i) there are novel designs of compact microwave filters
ii) there are novel designs of compact antennas
iii) the thesis has potentials for patents and future commercialisation.

Thank you.

Yours sincerely,

ASSOCIATE PROFESSOR DR. MAZLINA BINTI ESA
Department of Radio Communication Engineering
Faculty of Electrical Engineering
for The Dean
☎ : 07-5535262
e-mail : mazlina@fke.utm.my

“We hereby declare that we have read this thesis and in my opinion this thesis is sufficient in term of scope and quality for the award of the degree of Master of Engineering (Electrical)”.

Signature : ....

Supervisor : Associate Professor Dr Mazlina binti Hj Esa

Date : 28 December 2005.

Signature : ....

Co-Supervisor : Associate Professor Dr Jasmy bin Yunus

Date : 28 December 2005.

BAHAGIAN A – Pengesahan Kerjasama*

Adalah disahkan bahawa projek penyelidikan tesis ini telah dilaksanakan melalui kerjasama antara

______________________ dengan ______________________

Disahkan oleh:

Tandatangan : .... Tarikh : ....

Nama : ....

Jawatan : ....
(Cop rasmi)

* *Jika penyediaan tesis/projek melibatkan kerjasama.*

BAHAGIAN B – Untuk Kegunaan Pejabat Sekolah Pengajian Siswazah

Tesis ini telah diperiksa dan diakui oleh:

Nama dan Alamat
Pemeriksa Luar : **Prof. Madya Dr. Zainol Abidin B Abd Rashid**
Fakulti Kejuruteraan
Universiti Kebangsaan Malaysia
43600 UKM, Bangi
Selangor Darul Ehsan

Nama dan Alamat
Pemeriksa Dalam I : **Dr. Mohamad Kamal B Abd Rahim**
Fakulti Kejuruteraan Elektrik
UTM, Skudai

Pemeriksa Dalam II :

Nama Penyelia lain :
(jika ada)

Disahkan oleh Penolong Pendaftar di Sekolah Pengajian Siswazah:

Tandatangan : .... Tarikh : ....

Nama : **GANESAN A/L ANDIMUTHU**

A COMPACT S – BAND FRONT-END RECTENNA FOR WIRELESS POWER TRANSFER APPLICATION

IKHWAN PERANGGI POHAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARI 2006

ii

I declare that this thesis entitled *"A Compact S – Band Front-End Rectenna for Wireless Power Transfer Application"* is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not currently submitted in candidature of any other degree.

Signature : ....

Name : Ikhwan Peranggi Pohan

Date : 28 December 2005

To my beloved parents

ACKNOWLEDGEMENT

First and foremost, I would like to thank the Creator, ALLAH S. W. T. for giving me such an unbelievable strength to overcome all the obstacles during the completion of this research. In addition, my regards to Prophet Muhammad S.A.W. for guiding men to the straight path.

I would like to express my sincere appreciation to my main supervisor Associate Professor Dr. Mazlina binti Hj Esa for encouragement, guidance, advices and critics. I am also very thankful to my co-supervisor Associate Professor Dr. Jasmy bin Yunus for the valuable support. In addition, many thanks to Mrs. Noor Asniza binti Murad for her support.

I would like to thank all my teachers and lecturers for the shared knowledge. Many thanks to Ms. Rosmawati binti Othman, Mr. Adnall bin Bakar and other technicians for their sincere help. I would like to express thanks to Mr. Mohd. Fairuz bin Mohd. Yusof and all my friends for ideas, help and discussions.

I would also like to thank Dr. Berndie Strassner, Dr. Young-Ho Suh, Dr. Robert Cahill and Dr. Lung-Hwa Hsieh for short warm technical discussions.

Finally, I greatly appreciate my brothers, sisters, Mala and relatives for their spiritual support during my study.

ABSTRACT

A rectenna is used to receive transmitted power through space for wireless power transmission (WPT). This thesis presents the development of an S-band front-end microwave rectenna prototype elements operating at 2.45 GHz of industrial, scientific and medical (ISM) band. The microstrip front-end rectenna consists of an antenna and a low-pass filter (LPF). Both prototype elements were simulated. Optimized designs were fabricated and tested. For the antenna, two designs were investigated, i.e. corner-truncated square patch (CTSP) and slitted CTSP (SCTSP) fed by electromagnetic coupling. Size reduction of 37 % has been achieved through simulations for the SCTSP, compared to CTSP design at the operating frequency of 2.45 GHz. Measurement results showed that the antenna exhibits well matched impedance at the corresponding frequency of operation but with a slight shift of 123 MHz higher frequency as well as 2.5 dB higher axial ratio. SCTSP is proposed for the antenna candidate front-end rectenna. LPF was designed with elliptic function characteristic. Three designs were investigated for single element structure of 3rd order. These were stepped-impedance hairpin (SIH), meandered-gap hairpin (MGH) and over-coupled end meandered-gap hairpin (OCEMGH). Through simulations, size reduction of 28.6 % has been achieved for the MGH, compared to SIH. Both exhibit the same cutoff frequency. It was also found that higher cutoff frequency corresponds to lower insertion loss at 2.45 GHz. An impressive reduction in size of 60 % has been achieved for the OCEMGH, compared to SIH. The OCEMGH also exhibited better insertion loss at 2.45 GHz and rejection at 4.9 GHz and hence is proposed as the filter candidate for the front-end rectenna. Elliptic function LPF of 5th order was also designed. Two designs were proposed, i.e. unidentical cascaded hairpin (UCH) and identical cascaded hairpin (ICH). Simulated results showed that both filter have sharper cutoff frequencies compared to that of SIH. Measurement results showed that the five LPFs agree well with the simulated results.

ABSTRAK

Rektena digunakan untuk menerima kuasa yang dihantar melalui ruang bagi penghantaran kuasa tanpa wayar (WPT). Tesis ini membentangkan pembangunan elemen prototaip rektena gelombang mikro hujung-hadapan jalur-S yang beroperasi pada 2.45 GHz; jalur perindustrian, saintifik dan perubatan (ISM). Rektena mikrojalur hujung-hadapan terdiri daripada antena dan penapis lulus rendah. Kedua-dua elemen prototaip telah disimulasi. Rekabentuk optimum telah dibina dan diuji. Bagi antena, dua rekabentuk diselidiki, iaitu tampalan segi empat sama terpotong-sudut (CTSP) dan tampalan segi empat sama terpotong sudut terkelar (SCTSP). Kedua-duanya mempunyai suapan gandingan elektromagnet. Pengurangan saiz sebanyak 37 % telah diperolehi daripada hasil simulasi untuk SCTSP berbanding CSTP pada frekuensi kendalian 2.45 GHz. Hasil pengukuran menunjukkan bahawa galangan antena terpadan dengan baik pada frekuensi kendalian tetapi terdapat 123 MHz anjakan kecil frekuensi, begitu juga dengan nisbah paksi 2.5 dB yang lebih tinggi. Penapis lulus rendah direkabentuk dengan ciri fungsi eliptik. Tiga rekabentuk dicadangkan untuk element tunggal peringkat ketiga, iaitu pin rambut galangan berlangkah (SIH), pin rambut sela-berliku (MGH) dan pin rambut sela-berliku ganding-hujung-terlebih (OCEMGH). Pengurangan saiz sebanyak 28.6 % telah diperolehi bagi MGH daripada hasil simulasi berbanding SIH. Kedua-duanya mempunyai frekuensi potong yang sama. Frekuensi potong yang lebih tinggi didapati menghasilkan kehilangan sisipan yang lebih rendah pada 2.45 GHz. Pengurangan saiz yang menakjubkan sebanyak 60 % telah diperolehi oleh OCEMGH berbanding SIH. OCEMGH juga menunjukkan kehilangan sisipan pada 2.45 GHz dan penolakan pada 4.9 GHz yang lebih baik dan dicadangkan sebagai calon penapis pada rektena hujung-hadapan. Penapis lulus rendah fungsi eliptik peringkat 5 juga direkabentuk. Dua rekabentuk dicadangkan, iaitu susunan pin rambut kaskad tidak serbasama (UCH) dan pin rambut kaskad serbasama (ICH). Hasil simulasi menunjukkan kedua-dua penapis mempunyai frekuensi potong yang lebih tajam berbanding SIH. Hasil pengukuran menunjukkan bahawa kelima-lima penapis lulus rendah adalah setanding dengan hasil simulasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	:	Voltage ratio
a_1	:	Incident wave at port 1
a_2	:	Incident wave at port 2
ABCD	:	Matrix parameters
a_n	:	Incident wave at port n
B	:	Transfer impedance
b_1	:	Reflected wave at port 1
b_2	:	Reflected wave at port 2
b_n	:	Reflected wave at port n
c	:	Length of the perturbation section
c'	:	Speed of light
C	:	Transfer admittance
C_{3s}	:	Total capacitance of adjacent transmission line and shunt capacitances of hairpin resonator 1 and 2
C_a	:	Equivalent capacitance of the adjacent single transmission line
C_e	:	Even-mode capacitance
C_f	:	Fringe capacitance at the outer edge of the strip
C_f'	:	Fringe capacitance due to the presence of another line
C_g	:	Equivalent gap capacitance of coupled line
C_{ga}	:	Fringe capacitance for the air across the coupling gap
C_{gd}	:	Fringe capacitance for dielectric regions across the coupling gap
C_n	:	Scaled capacitor element
C_o	:	odd-mode capacitance
C_p	:	Parallel plate capacitance between the strip and ground plane
C_p	:	Equivalent shunt capacitance of coupled line
C_{p1}	:	Equivalent shunt capacitance of coupled line of resonator 1
C_{p2}	:	Equivalent shunt capacitance of coupled line of resonator 2

C_{ps}	:	Sum of the capacitance of single transmission line, coupled line and step width discontinuity
C_s	:	Equivalent capacitance of single transmission line
C_{s1}	:	Equivalent capacitance of single transmission line of resonator 1
C_{s2}	:	Equivalent capacitance of single transmission line of resonator 2
C_{Δ}	:	Step width discontinuity
d	:	Maximum dimension of antenna
D	:	Current ratio
E	:	Electric field
E_{x}	:	Electric field in x direction
E_{y}	:	Electric field in y direction
f_c	:	Cutoff frequency
f_{c2}	:	$\|S_{21}\|$ 3-dB point again after f_c
f_{cCP}	:	Frequency with minimum axial ratio
f_H	:	Higher cutoff frequency
f_L	:	Lower cutoff frequency
f_r	:	Operating frequency
G_r	:	Radiation conductance
g_0	:	Input terminal impeance
g_{Cn}	:	Prototype element value of capacitor
g_{Ln}	:	Prototype element value of inductor
g_{n+1}	:	Output terminal impedance
H	:	Magnetic field
h	:	Thickness of substrate
i	:	Numbers of the corrugated in the left line of the coupled line
I_1	:	Current at port 1
I_2	:	Current at port 2
I_L	:	Insertion loss between ports n and m
j	:	Numbers of the corrugated in the right line of the coupled line
L	:	Length of patch
L_A	:	Insertion loss
L_t	:	perturbed side length
L_1	:	Distance from feed point to the left edge of the patch
L_2	:	Distance from feed point to the right edge of the patch
l_a	:	length between bottom-left-end-gap and the nearest meander section
l_b	:	length between top-left-end-gap and the nearest meander section

l_d	:	length between bottom-right-end-gap and the nearest meander section
l_e	:	length between top-right-end-gap and the nearest meander section
l_x	:	length of external meander section
l_y	:	axial length of longer meander section
l_z	:	length of internal meander section
L_{Ar}	:	Passband ripple
L_{As}	:	Minimum stopband insertion loss
l_c	:	Length of the coupled line
l_{c1}	:	Length of the coupled line of resonator 1
l_{c2}	:	Length of the coupled line of resonator 2
L_n	:	Scaled inductor element
l_o	:	Length of the over-coupled end
L_s	:	Equivalent inductance of single transmission line
l_s	:	Length of single transmission line
l_{s1}	:	Length of single transmission line of resonator 1
l_{s2}	:	Length of single transmission line of resonator 2
l_{sl}	:	Length of slit
n	:	Filter order
OA	:	Major axis
OB	:	Minor axis
P_{dB}	:	Cross polar level
P_{roc}	:	Open circuit reflected power
P_{rsc}	:	Short circuit reflected power
P_r	:	Device under test reflected power
P_i	:	Input power
P_1	:	Power from direct connection
P_2	:	Output power from inserted device
Q	:	Quality factor
R	:	Far-field distance
R_L	:	Return loss at port n
S'	:	Total area of the patch
S	:	Band designation for 2 GHz to 4 GHz
s	:	Gap of the coupled line
s'	:	Overlap distance of EMC feed
S	:	Scattering
S_{11}	:	Input reflection coefficient

S_{12}	:	Reverse transmission coefficient
S_{21}	:	Forward transmission coefficient
S_{22}	:	Output reflection coefficient
t	:	Thickness of conductor
V_1	:	Voltage at port 1
V_2	:	Voltage at port 2
W	:	Width of patch
w	:	Width of microstrip line
w_a	:	Width of the adjacent single transmission line
w_c	:	Width of coupled lines
w_s	:	Width of single transmission line
w_{sl}	:	Width of slit
w_x	:	axial width of shorter meander section
Y_c	:	Admittance of equivalent capacitance of single
Y_g	:	Admittance of gap capacitance of coupled lines
Y_L	:	Admittance of equivalent inductance of single
Y_p	:	Admittance of shunt capacitance of coupled lines
Y_s	:	Admittance of single transmission line
Z_0	:	Characteristic impedance
Z_{0e}	:	Even-mode characteristic impedance
Z_{0o}	:	Odd-mode characteristic impedance
Z_{in}	:	Input impedance
Z_L	:	Impedance of inductor
Z_s	:	Characteristics impedance of the single transmission line
ΔL	:	Line extension
Δs	:	Total area of the perturbation segment
β_c	:	Phase constant of the coupled line
β_e	:	Phase constant of even-mode
β_g	:	Propagation constant
β_o	:	Phase constant of odd-mode
β_s	:	Phase constant of the single transmission line
ε	:	Ripple constant
ε_r	:	Relative dielectric constant
ε_{re}	:	Effective dielectric constant
ε_{re}^{e}	:	Effective dielectric constant of even-mode

ε_{re}^{o}	:	Effective dielectric constant of odd-mode
ε_{rt}	:	Total dielectric constant
Γ	:	Reflection coefficient
λ	:	Wavelength
λ_0	:	Free space wavelength
τ	:	Tilt angle of the ellipse
δ	:	Loss tangent
Ω	:	Frequency (rad/s)
Ω	:	Ohms
Ω_c	:	Cutoff frequency
Ω_{c1}	:	Low cutoff frequency
Ω_{c2}	:	High cutoff frequency
Ω_s	:	Ratio of equal-ripple stopband starting to cutoff frequency
ω	:	Angular frequency
ω_c	:	3-dB cutoff angular frequency
θ	:	Elevation angle
φ	:	Azimuth angle

LIST OF ABBREVIATIONS

AR	:	Axial ratio
BPF	:	Band-pass filter
BW	:	Bandwidth
CCL-SCTSP	:	Counterclockwise L-shaped slits SCTSP
CIR	:	Circulator
CL-SCTSP	:	Clockwise L-shaped slits SCTSP
CP	:	Circular polarization
CPS	:	Coplanar strip line
CTSP	:	Corner-truncated square patch
dB	:	Decibel
dBd	:	Decibel over half-wave dipole radiator
dBi	:	Decibel over isotropic radiator
DFL-SCTSP	:	Direct facing L-shaped slits SCTSP
DL-SCTSP	:	Double L-shaped slits SCTSP
DRLA	:	Dual rhombic loop antenna
DVM	:	Digital voltmeter
EDA	:	Electronic design automation
EF	:	Elliptic function
EM	:	Electromagnetic
EMC	:	Electromagnetic coupling
HPBW	:	Half power beamwidth
ICH	:	Identical cascaded hairpin
ISM	:	Industrial, scientific and medical
LHCP	:	Left-hand circularly polarized
LPF	:	Low-pass filter
MGH	:	Meandered-gap hairpin
OCEH	:	Over-coupled end hairpin

OCEH_L	:	Left over-coupled end hairpin
OCEH_R	:	Right over-coupled end hairpin
OCEMGH_L	:	Left over-coupled end meandered-gap hairpin
OCEMGH_R	:	Right over-coupled end meandered-gap hairpin
OP-AMP	:	Operational Amplifier
PCB	:	Printed circuit board
Rectenna	:	Rectifying antenna
RHCP	:	Right-hand circularly polarized
SCTSP	:	Slitted corner-truncated square patch
SCTSP_C	:	SCTSP fed by coaxial feed
SCTSP_E	:	SCTSP fed by electromagnetic coupling feed
SIH	:	Stepped-impedance hairpin
SP	:	Square Patch
TEM	:	transverse electromagnetic
UCH	:	Unidentical cascaded hairpin
VCO	:	Voltage controlled oscillator
VSWR	:	Voltage standing wave ratio
WPT	:	Wireless power transmission

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

A wireless power transmission (WPT) system refers to a system whereby electric power is transmitted from one point to another through the vacuum of space or the earth̊s atmosphere w ithout the use of wires or any substance. The power in space would be in microwave or laser beams. The laser has an advantage of having small beam divergence. However, the efficiencies in generating the laser beam and converting it back into electrical energy are low compared with microwave [1, 2]. Therefore, the development of power transmission system using microwave beam is more attractive.

WPT is one of the most useful applications of radio waves. The concept of beamed microwave power transmission is important where it is not feasible to transmit power from one place to another by traditional transmission and distribution system. The most abundant and sustainable source of energy for mankind is the sun. Solar energy is difficult to be used directly on earth, because of its low density, and its lack of regularity due to weather condition and day-and-night cycles. To solve this problem, Glaser proposed an idea of orbiting satellites in geosynchronous

equatorial orbit to collect the unlimited sunlight, converting the solar energy and transmitting the energy through microwave to earth, called Solar Power Satellites (SPS) [2]. On the earth, the microwave will be rectified and transformed to utility power for public use. This power then can be transmitted wireless from one point to another directly or by power relay satellites through microwave.

Malaysia has a large area of relatively undeveloped land near the equator in Sarawak where many people still live without electricity. Because of this, Malaysia is a potential place to be a rectenna site. The WPT is also an alternative method of energy transmission in Malaysia. In addition, the UTM Skudai campus has been identified as a rectenna test bed for implementing the WPT concept. The campus is located very near to the equator.

One of the key components in a WPT system is a rectenna at the receiving end [3, 4]. The block diagram of a rectenna is shown in Figure 1.1 which consists of an antenna, low-pass filter (LPF) and rectifying circuits. The front-end of a rectenna is an antenna and LPF. The LPF inserted between the antenna and the rectifying circuit needs to be designed so that the fundamental frequency can be passed and a portion of the higher order harmonics generated from the rectifying circuit be rejected back to the rectifying circuit [5].

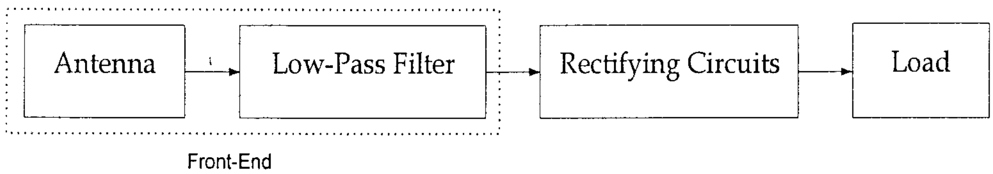


Figure 1.1 Block diagram of a rectenna circuit connected to a load.

1.2 Problem Statement

Power can be wirelessly delivered from one point to another by using microwave frequency. In a WPT system, a rectenna is used to receive the transmitted power through space and converting the power to dc power, hence, it can be used for energy storage. Two important components of the front-end rectenna are the receiving antenna and the adjacent low-pass filter. There is an immediate need to develop a single front-end rectenna prototype which is useful for terrestrial WPT reception.

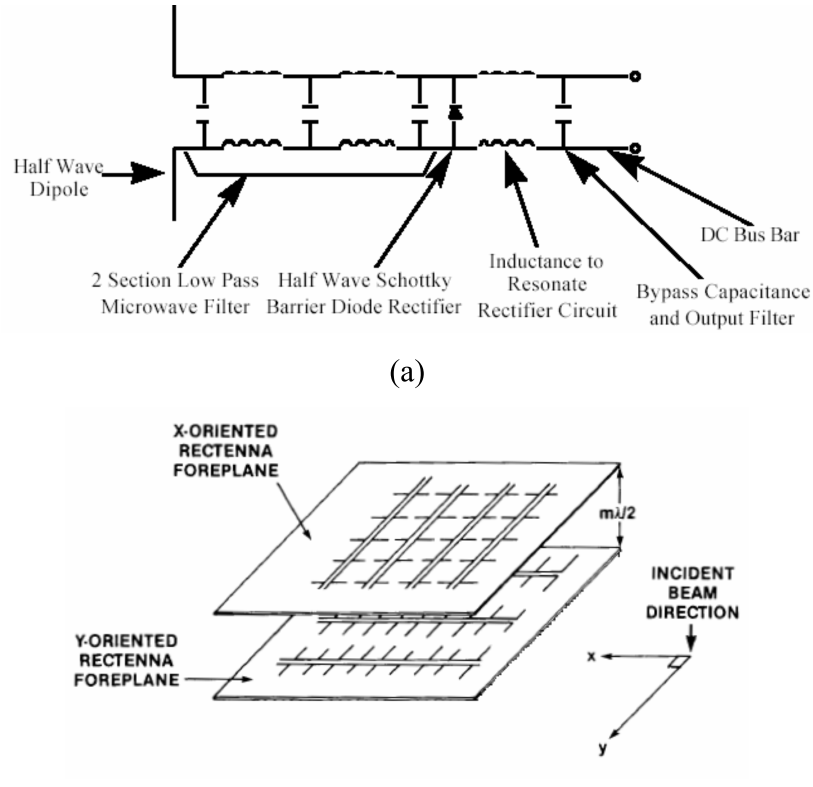
To eliminate the need to orient the antennas between the transmitter and the receiver, the receiving antenna has to be circularly polarized. Hence, the rectenna may be rotated without significantly changing the output voltage. Besides that a compact antenna is desired which corresponds to lightweight device and cost effectiveness of fabrications.

Low passband insertion loss, sharp cutoff frequency steepness and high stopband rejections are desirable elliptic function filter response. Beside that, compactness in the design is desirable for cost effectiveness of fabrications.

1.3 Front-end Rectenna Review

Since the early 1960s, rectennas have been researched and developed. Brown was a pioneer in developing the first 2.45 GHz rectenna [3]. The front-end rectenna consists of an aluminium bar half-wave dipole antenna and LPF. Besides being a filter, the LPF is used as an impedance matching between the antenna and the rectifying circuit. Figure 1.2(a) shows the schematic of the rectenna. Later, Brown

and Triner [6] developed a thin-film printed ~~c~~ircuit dipole rectenna to reduce the weight. In [7], dual polarization rectenna was developed to receive power from transmitted beam of two orthogonal polarizations. Hence, the power received will be maximum. The antenna was realized by two thin-film dipole orthogonal linearly polarized foreplane in Xand Y orienta tions separated by a multiple of half-wavelength distance to achieve dual polarization as shown in Figure 1.2(b). The basic antenna was employed from [6]. However, this geometry has a bulky structure due to using two orthogonal antennas to achieve dual polarization.



(a)

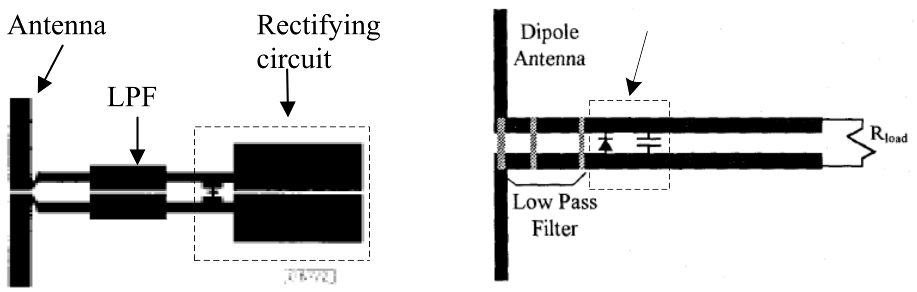
(b)

Figure 1.2 (a) Schematic of a half-wave dipole rectenna [3] (b) Dual polarization two orthogonal thin-film dipole antennas of a rectenna [7].

A rectenna element using a microstrip dipole antenna operating at 35 GHz has been developed [8]. Figure 1.3(a) shows the circuit configuration of the rectenna. The rectenna has a coplanar strip line LPF which consists of three transmission line sections to connect the antenna and the rectifying circuit. The LPF is of a stepped-impedance LPF having a Butterworth or Chebyshev response. The

rectenna in this design has two filter sections similar to [3, 6, 7]. The LPF structure is space consuming.

A dipole rectenna has been developed by [9, 10]. In [9], the rectenna operates at 5.8 GHz and is shown in Figure 1.3(b). In this design, the LPF composed of three printed strips on the opposite of the coplanar strip line transmission line. The rectenna has only one section of LPF and the coplanar strip line has an advantage of allowing ease mounting of the rectifying circuit devices. The cutoff frequency of the LPF was located between the fundamental frequency (to pass the operating frequency) and the second order harmonic (to reject the higher harmonics). The design of a single section LPF is interesting as the whole design can be made compact. The filter proposed in this thesis employs such design.

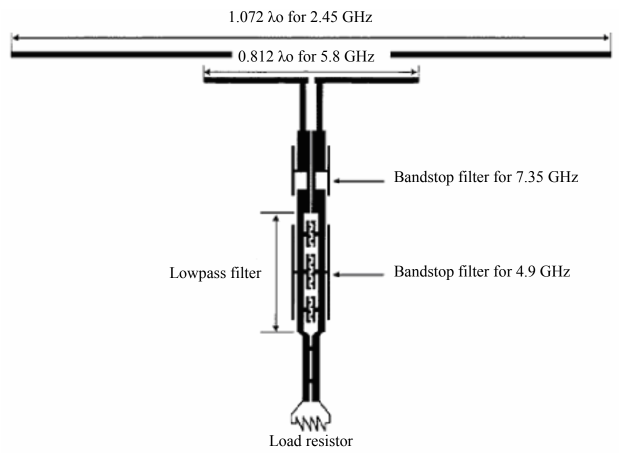


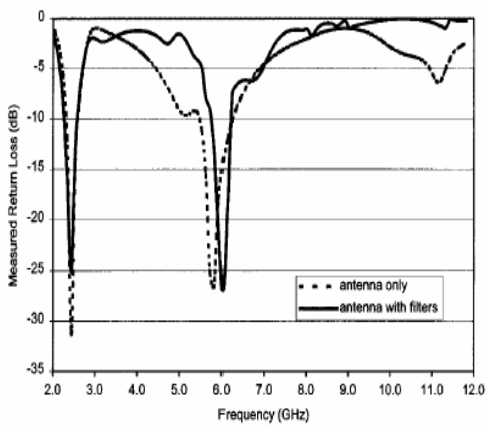
(a) (b)

Figure 1.3 (a) circuit configuration of a 35 GHz dipole rectenna [8] (b) 5.8 GHz dipole rectenna element [9].

A dual-frequency printed dipole rectenna has been developed for WPT at 2.45 GHz and 5.8 GHz [11]. The antenna consists of 2 dipoles as shown in Figure 1.4(a). The long dipole operates at 2.45 GHz while the short dipole operates at 5.8 GHz. The filter circuit in this design has a coplanar strip line (CPS) LPF integrated with a bandstop filter. The LPF has a cutoff frequency of 7 GHz to pass 2.45 GHz and 5.8 GHz frequencies while rejects 11.6 GHz which is the second order harmonic of 5.8 GHz. However, the LPF will also pass the 4.9 GHz and 7.35 GHz frequencies which are the second and third order harmonics of 2.45 GHz. To reject these harmonics, a bandstop filter is introduced to the filter circuit. The measured

frequency responses of the antenna and the antenna with filter are shown in Figure 1.4(b). This rectenna can be used for WPT at either frequency depending upon power availability at 2.45 GHz or 5.8 GHz. However, the presence of two filters increases the bulkiness of the rectenna.





(a) (b)

Figure 1.4 (a) Circuit configuration of the dual-frequency dipole rectenna (b) measured frequency responses of the antenna and the antenna with filters [11].

A circular patch antenna has been designed for dual polarized rectenna at 2.45 GHz [12]. The antenna is fed 90^{o} apart by two transmission line feeds at the edges of the antenna to achieve dual polarization as shown in Figure 1.5. The LPFs are attached at the two feed lines. The LPFs can be the stepped-impedance LPF having a Butterworth or Chebyshev response. This configuration, however, increases the bulkiness of the front-end rectenna.

A circular patch was also employed [13]. Figure 1.6 shows the configuration and the cut plane view of the rectenna. The rectenna was constructed on two layer substrates and operates at 5.8 GHz. The antenna was fed by a pin near the centre of the patch to minimize the area of the feeding circuit and leads to a linearly polarized. In this design, the LPF was included in the rectifying circuit and placed at the rear side of the rectenna. The LPF is of stepped-impedance as shown in Figure 1.6(b).

The overall thickness of the rectenna element is 2.4 mm which is slightly bulky for mobile application. In addition, the feed pin increases the difficulty of fabrication and decrease the cost effectiveness of the rectenna.

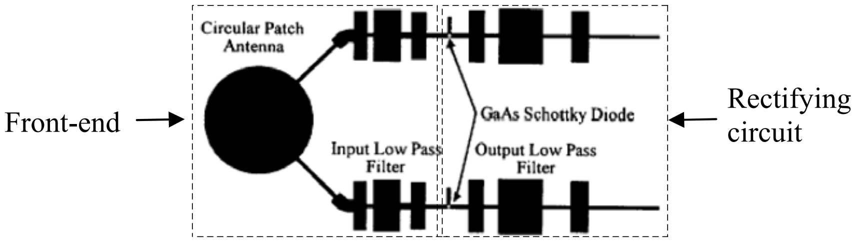
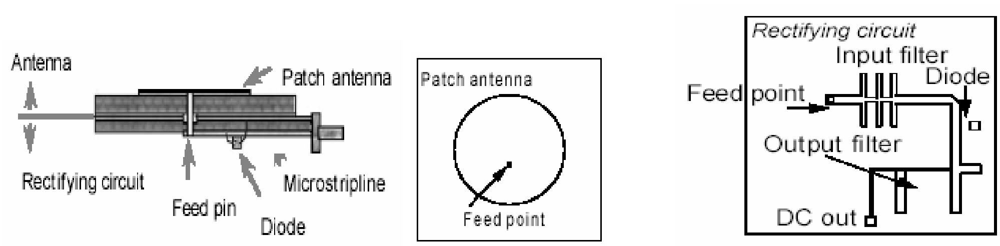


Figure 1.5 The configuration of dual polarized circular patch rectenna [12].

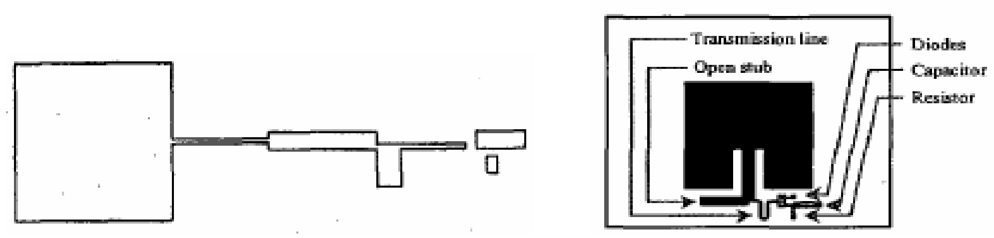


(a) (b)

Figure 1.6 (a) Cut plane view and configuration of the antenna (b) rectifying circuit configuration [13].

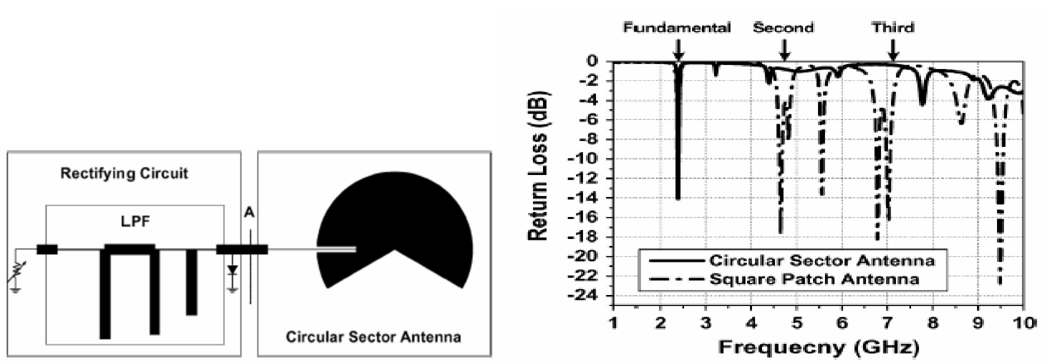
A square patch microstrip antenna has been employed to construct the rectenna [14]. The antenna was fed by a microstrip line. Microstrip LPF of 3^{rd} order with Chebyshev response was used as the filter. The disadvantage of this design is its microstrip antenna patch size. Figure 1.7(a) shows the configuration of the rectenna element. A similar square patch was developed with an inset feed microstrip line to reduce the size of the rectenna [15]. It was found that the inset does not significantly affect the resonant frequency but it modified the input impedance. However, this design does not have a filter circuit to block the higher harmonics from the rectifier circuit which leads to degradation of the rectenna performance. Figure 1.7(b) shows the corresponding rectenna layout.

A rectenna designed with a microstrip harmonic-rejecting circular sector antenna at 2.4 GHz has been proposed [16, 17]. Compared to the square patch antenna, the circular sector antenna using inset feed exhibits high reflection coefficient at the second and third harmonics. Because of this, the LPF between the antenna and rectifying circuit can be eliminated. In addition, the antenna exhibits linearly polarized wave. The configuration of the rectenna with a microstrip circular sector antenna and the measured return losses of the microstrip circular sector and square patch antennas are shown in Figure 1.8.



(a) (b)

Figure 1.7 (a) Square patch rectenna with microstrip feed line [14]
(b) square patch rectenna with microstrip inset feed line [15].



(a) (b)

Figure 1.8 (a) Configuration of the rectenna with a microstrip circular sector antenna (b) measured return losses of the microstrip circular sector and square patch antennas [16].

In the last seven years, researchers have been focused on circularly polarized rectenna. Compared to the linearly or dual polarization, the circular polarization can eliminate the need to orient the antenna, reduce the effects of multipath and maximize the received signal. Hence, the rectenna can be rotated while maintaining receiving constant power. Planar dual-patch antenna has been used to achieve circularly polarized rectenna [18]. Dual identical almost quadratic patch has been proposed. Figure 1.9 shows the layout of the circularly polarized dual-patch rectenna. However, the rectenna is bulky due to having two patch antennas and has no LPF to reject the higher harmonics flowing back into the antenna.

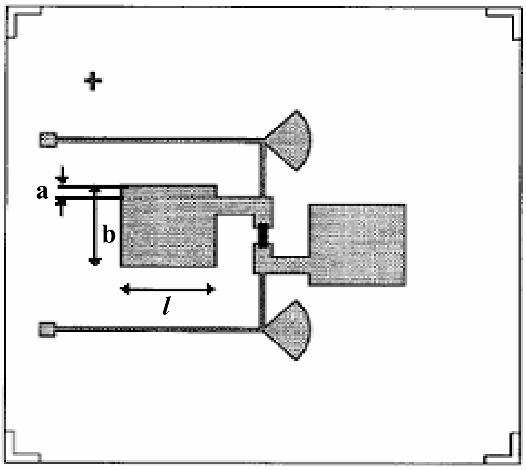
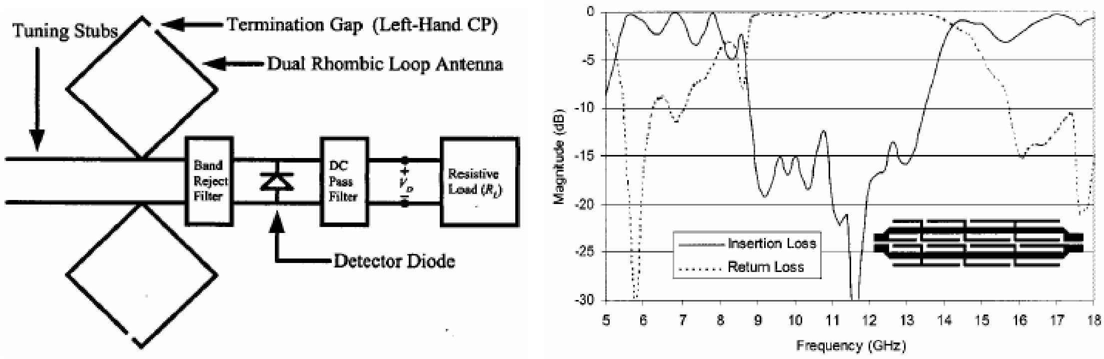


Figure 1.9 The layout of circularly polarized dual-patch antenna [18].

A 5.8 GHz rectenna using a dual rhombic loop antenna (DRLA) has been developed [19]. This antenna exhibits circular polarization. Circular polarization is achieved by having two gap positions of DRLA. The positioning of the gaps, as shown in Figure 1.10, yields left-hand circular polarization. If the gaps are mirrored to the opposing sides of the antenna, the DRLA will become a right hand circular polarization. The CPS tuning stubs tune out the imaginary impedance in order to yield a real impedance at the antennas̊ inpu t terminals and allow single rectenna element to be connected to other rectennas to form an array. The advantages for using DRLA are high gain, wideband performance and fabrication simplicity. The rectenna used a CPS band-reject filter to suppress the reradiated harmonics flowing from the diode to the antenna. Figure 1.10 shows the rectenna block diagram and the

simulated band-reject filter frequency response. The focused harmonic to be suppressed by the filter is the second harmonic. This is because higher harmonics are not significant as the second harmonic [5]. However, the CPS band-reject filter has a complicated design structure.



(a) (b)

Figure 1.10 (a) Rectenna block diagram (b) Simulated band-reject filter [19].

A circularly polarized rectenna using a shorted annular ring-slot antenna operating at 5.8 GHz has been proposed [20]. Figure 1.11 shows the layout of the rectenna. The antenna is fed from the bottom layer with a transmission line and two quarter-wave transformers to match to the rectifier circuit. This leads to increasing the size of the rectenna. In addition, the rectenna does not have any filter circuit between the antenna and the rectifier circuit for filtering out the higher order harmonics.

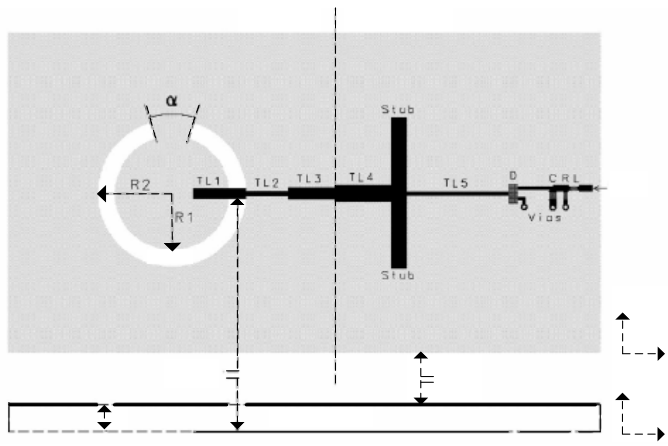


Figure 1.11 The layout of the shorted annular ring-slot rectenna [20].